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The theoretical analysis and experimental research on multiple incremental forming to raise formability

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Abstract. Incremental forming with a high degree of flexibility and without special tool is suitable for small quantity, variety and rapid prototyping. It is a very promising technology of sheet forming. The incremental forming of straight-wall parts is difficult. Generally multistage forming method is used in straight-wall parts forming. According to the plastic forming theory and incremental forming mechanism, the method of calculation of the forming stages n is drawn. The n is calculated according to the two formula for a vertical wall square box. The process analysis and experimental verification are done. The best scheme is determined to verify the validity of formulas and multi-pass incremental forming technology. It is a great significance for practical application.

Key words. Incremental forming, sheet forming, metal forming, flexible process, forming stages.

1. Introduction

The incremental forming with high flexible degree and without special molds can improve the formability of sheet metal, suitable for small quantity, variety and rapid prototyping. It is a very promising technique of sheet forming. In the early 90's, S.Matsubara [1] develop a method that forms metal sheets into three-dimensional shapes without using dedicated dies. For this purpose, very simple and compact tooling is devised and put on the bed of a numerically controlled (NC) machine tool. It can be controlled with an NC program, which is made by commercial CAD/CAM (computer aided design/manufacture) systems.

But the research is still in the lab, not widely used in the industrial production.

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One of the major problems include [2]: namely the limitation on the maximum achievable wall angle, and the occurrence of geometric deviations.

In order to overcome these problems, many scholars have been studying. M. Ham and J.Jeswiet [3] present a new experimental data on forming limits in single point incremental forming (SPIF),which is a sheet metal forming process which does not require dies. In this experimental work, new results are presented as graphical response surfaces which show the forming limit for all the critical factors listed previously. In addition, forming limits are presented in terms of forming limit diagrams.

G.Ambrogio [4] shows that SPIF permits a relevant increase of formability limits, just as a consequence of the peculiar deformation mechanics. The research is focused on the theoretical investigation of process mechanics; the aim was to achieve a deeper understanding of basic phenomena involved in SPIF which justify the above mentioned formability enhancing.

Z.Cui and L.Gao[5] investigate incremental forming with three forming strategies to produce prototype parts with hole-flanges. Results indicate that the forming strategy by increasing the part diameter in small steps during the forming process reaches the final optimum part geometry to improve the formability while it can produce a relatively higher neck height, maximum forming limit ratio (LFRmax), and uniform wall thickness. Also this strategy can be fine tuned to control the thinning band such that fracture can be avoided.

T.J.Kim and D.Y.Yang [6] show by the experiments that a sheet blank is mainly subject to shear-dominant deformation. Therefore, the final thickness strain can be predicted. The uniformity of thickness throughout the deformed region is one of the key factors to improve the formability in the sheet metal forming processes. Using the predicted thickness strain distribution, the intermediate geometry is decided in the manner that a shear deformation is restrained in the highly shear-deformed region and vice versa. This double-pass forming method is found to be very elective so that the thickness strain distribution of a final shape can be made more uniform.

H.Iseki and T.Naganawa[7]has developed a multistage incremental sheet metal bulging machine using spherical and cylindrical rollers for vertical wall surface forming of rectangular shallow shells. The multistage incremental forming comprises three operations: bulging with a spherical roller, right angle forming and flattening with cylindrical rollers. The hand-operated bulging machine formed a vertical wall surface, which is highly precise and preferred by designers. A method of calculating for the approximate distribution of thickness strain and the maximum bulging height of the rectangular panel was proposed using the deformation limit diagram obtained from the incremental bulging test with a ball roller and a geometrical plane-strain deformation model with a constant strain gradient. The predictions for the rectangular shell were reasonably in good agreement with experimental values for the annealed aluminum sheet.

There were some studies on the effect of some factors, such as stepping rates and material properties, on the dimensional accuracy of specimens in single-stage incremental forming [8,9]. However, the previous studies only considered the effect of these parameters on the dimensional accuracy of the local region. Therefore, G.Hussain et al.[10] investigated further the effect of material properties, such as hardening exponent and equivalent blank stiffness, on the whole profile accuracy, and H.Lu et al. adopted a model predictive control strategy to eliminate availably the dimensional deviation caused by the pillowing tendency of materials.

Although researchers have made a lot of efforts, but for multiple pass incremental forming is not a perfect method. The forming stages n has a significant impact, but few studies.

In this study, based on the plastic forming theory and incremental forming mechanism, the calculation method of forming stages n is researched. A case study of vertical wall square box forming is done to verify the validity of formulas and multi-pass incremental forming technology.

2. The incremental forming principle

The incremental forming principle shows in Figure 1. The forming system consists of the forming tool, pin, support plate, the support model and so on. The forming tool moves under the control of the NC system, the support model can be used in a simple mold for the complex shape parts. Before the forming, the blank will be put on the support model with clamping the four sides of the plate. The support plate can slide along the guide pin from top to bottom, as shown in Figure1a. The device is then fixed on the three axes NC machine tool. During the forming, the forming tool goes to the specified location according to the instructions of the control system. The sheet blank is shaped, as shown in Figure 1b. After the first layer of the profile is formed, the second layer is made until the entire workpiece forming is complete.

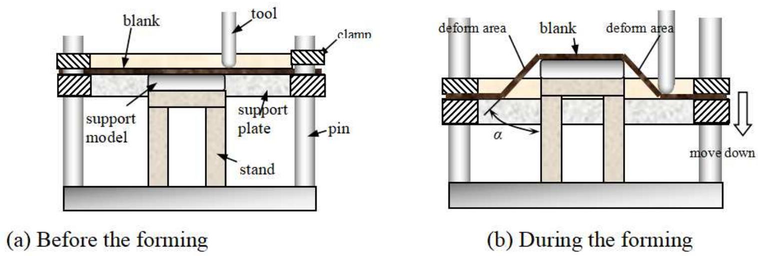

Fig. 1. Diagram of the incremental forming principle

3. The thickness analysis of the cone

The thickness analysis of the square box shows in Figure 2. During the forming, the forming tool will round along the z-axis direction to move down on a mandrel with the half cone angleα, forming a cone. The rectangular section slips into a parallelogram after the forming. According to the plastic deformation law of constant volume, the rectangular volume should be equal to the volume of the parallelogram, that is,

$$t_0 \cdot s_0 = t \cdot s \tag{1}$$

Where, t_0 is the initial thickness of the sheet, s_0 for the blank ring's surface area in the AB area, t for the thickness, s is the surface area after AB area sliding into a parallelogram A_1B_1area ,as shown in Figure 2.

$$s_0 = s \cdot \sin\alpha$$

$$t_0 \cdot s \cdot \sin\alpha = t \cdot s$$

$$t = t_0 \sin\alpha \tag{2}$$

According to (2), the material thickness change follows the sine law.

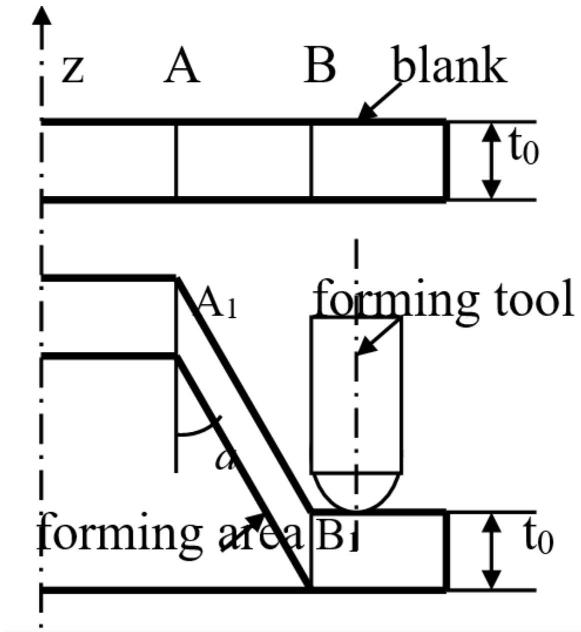

Fig. 2. Diagram of the square box forming

4. The pass design of multiple pass incremental forming

For those complex and steep wall workpieces with single-stage incremental forming process, wall thickness change, surface quality, dimensional accuracy and strength properties do not meet the requirement. For straight-wall parts with a half angle 0?, according to the sine law mentioned in the previous section, the sheet thickness is zero with single-stage incremental forming. Therefore, in recent years, studies on side walls are steep, complex shape and even straight-wall wall thickness have become a hot issue.

Multiple stages incremental forming technology is mainly used in a complex and a small half cone angle processing. In that case, in order to form appropriately, just a calculation method of pass number n need be figured out. Two calculation methods are listed below.

4.1. Passes algorithm based on thinning ratio of sheet metal

According to the law of Sines, the relation between reduction ratio and half cone angle is as follows:

$$\psi = \frac{t_0 - t}{t_0} = 1 - \sin\theta \tag{3}$$

The relation between various stages thickness reduction ratio and overall thinning ratio of wall thickness should be as follows:

$$\psi_1 + \psi_2 + \cdots + \psi_n = \psi_0 \tag{4}$$

If it is assumed that each reduction ratio for the average, then passes n can be calculated from the equation:$n\psi_a = \psi_0$,

$$n = \frac{\psi_0}{\psi_a} \tag{5}$$

4.2. Passes algorithm based on forming limit of sheet metal

For single stage and multistage incremental forming, the limit of the same material is constant. The limit is as follows: As shown in Figure 3a, the workpiece with a height h, the limit strain of single pass incremental forming is as follows:

$$\varepsilon_{\max} = \ln \frac{L_{AD}}{L_{OD}} = \ln \frac{1}{\sin\theta} \tag{6}$$

where, θ is a limit half cone angle.

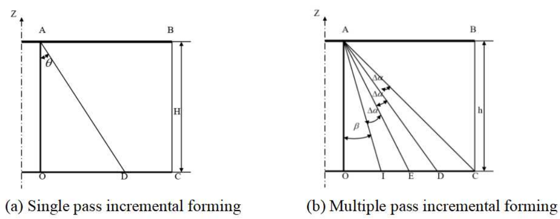

Fig. 3. The incremental forming tool-paths

Multi-pass incremental forming schematic is shown in Figure 3b, the total limit of plastic strain for the workpiece is:

$$\begin{aligned} \varepsilon_{\max} &= \ln \frac{L_{AI} + L_{IC}}{L_{AB}} \\ &= \ln \frac{\frac{h}{\cos\beta} + h\tan[(n-1)\Delta\alpha + \beta] - h\tan\beta}{h\tan[(n-1)\Delta\alpha + \beta]} \end{aligned} \tag{7}$$

Where, the minimum surfaces forming angles β (namely, the minimum angle between workpiece surfaces and tangent direction of the z axis), each forming angles decreases$\Delta\alpha$, the forming high h, the smallest stage number n.

Assuming the deformations of the parts (that is, the angle $\Delta\ \alpha$ decreases) are uniform, so multi-pass incremental forming critical times n can easily be calculated by following formula:

$$\mathrm{Y} = \mathrm{W} * \mathrm{X} = [w_1, w_2, \ldots\ldots, w_n] * \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ \mathrm{X_n} \end{bmatrix} \tag{8}$$

5. The thickness analysis of the formed straight-wall square box

The thickness changes of the straight-wall parts in multi-pass forming with a feed rate p is analyzed. The deformation assumes uniform. The analysis chart with a two-step tool path shows in Figure 3.The original thickness of the sheet AB $t_0 = 1.0$mm; the half cone angle for the first stage $\alpha_1 = 45°$;the thickness AD=t_1;the half cone angle for the second stage, that is, straight wall, the thickness $t_2$of deformation zone AC and CD. After the forming, at a first step, AB into AD, thickness from t_0 to t_1. According to the sine law, it can be obtained:

$$t_1 = 0.7071 t_0 \tag{9}$$

At the second step, AD into ACD, thickness from t_1 to t_2. According to the sine law, $t_2 = 0.7071t_1$, it can be got into(9), AC straight wall thickness:

$$t_2 = 0.7071 t_1 = 0.5 t_0 = 0.5$$

6. Tool path design of the vertical wall square box forming

In the incremental forming process, the thickness (t) of the deformed region is connected with the angleθbetween sheet metal forming surface and vertical direction z, the relationship between them conforms to the sine law, i.e.,$t = t_0 \sin\theta$, shown as Figure 1. The sine law indicates that the thickness of the deformed region is close to zero when the half-apex angle$\theta$of the box is close to zero. Therefore, the vertical wall square box can't be formed by NC incremental sheet metal forming process in a single process.

To overcome the difficulty, a method is designed to form vertical wall square box, through which a square conical box is gradually processed into vertical wall square box by multi tool paths. The tool paths are designed, as shown in Figure 4.

The tool path in the lower layer locus is parallel to that in the upper locus, and the height of the formed vertical wall is simultaneously the same as pitch h. First,θ is calculated to meet the condition that the vertical wall box isn't cracked. According to the designed forming locus, as shown in Figure 4d, the square conic box is formed atθ, as shown in Figure 4a. When this layer is finished, the forming tool moves down

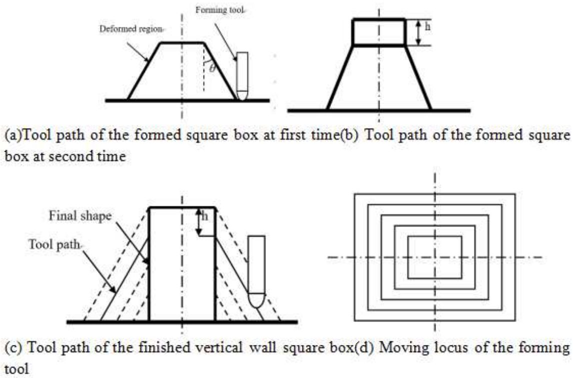

Fig. 4. Tool path diagram of the formed vertical wall square box

a small pitch h along the z-axis and continues to process the next layer until next layer is formed, as shown in Figure 4b. Finally, the vertical wall square box is formed from conical box by incremental forming with parallel line type multi tool-paths, as shown in Figure 4c.

7. Experiment

The experiment apparatus is composed of the forming tool, support model, support frame, blank holder, CNC machine, and so on. The forming tool has a hemispherical head of 10mm diameter which is fastened in the chuck of CNC machine. The tool is made of high carbon tool steel and polishes. The sheet metal is hard aluminum (2A12) sheet (t=1.0 mm). The test specimens are sheared to a square with width of 330 mm. The formed vertical wall square box has side length of 100 mm and height of 50 mm. A lubricant is coated on both the forming tool and the blank.

According to the geometrical shape of the vertical wall square box, the model is modelled by UG, and the G-code of tool-path is generated on the basis of the process planning. According to the process planning and G-code generated, the vertical wall square box is formed as shown in Figure 5.

(a) Deformed conic box (b) Square box during forming (c) Finished square box

Fig. 5. Pictures of vertical wall square boxes in incremental forming

8. Conclusions

According to sine law and$\varepsilon$of the deformed region, a vertical wall square box can't be finished by incremental forming with a single stage process, it must be formed with multi-stage processes. According to the plastic forming theory, the calculation method of the smallest number n is drawn. Analyzing the vertical wall cylinder parts forming, the minimum pass n is obtained, and the approach is verified by the experiment.

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